QSO HOSTS AND COMPANIONS AT HIGHER REDSHIFTS

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ABSTRACT

This review presents the current state of work on QSO hosts and companions at redshifts above 1. This includes the properties of QSO host galaxies, such as size, scale length, and luminosity, and morphology, as they appear to change with redshift and radio activity. This leads to a view of how the properties of galaxies that host QSOs change with cosmic time. I also review studies of the galaxy companions to QSOs at higher redshifts, and studies of the emission line gas in and around higher redshift QSOs. These topics should see great progress in the next decade.

1. Host galaxy detection

In the past decade we have made significant progress in detecting and measuring the host galaxies of QSOs at redshifts in the range 1 to 2.5, and even above 3 in a few instances. This is partly due to the fact that the hosts at higher redshifts are in very active star-forming stages of their lives, and are thus bright in the observed rest-frame UV. The first significant paper on high redshift host galaxies came from KPNO data with resolution only about 1.3 arcsec, showing dramatically that radio-loud hosts were both bright and large (Heckman et al 1991). Since then the availability of NIR imaging and higher resolution imaging (via HST or adaptive optics) have been responsible for the bulk of the higher z investigations to date, and which I attempt to review here (see e.g. Lowenthal et al 1995, Lehnert et al 1992, Hutchings 1995b, Aretxaga et al 1998, Hutchings 1998, Hutchings et al 1999, Lehnert et al 1999, Rix et al 2000, Kukula et al 2000, Ridgway et al 2001). It is clear that the use of 8-10m class telescopes will help us reach to fainter details and higher redshifts where redshift dimming dominates, and will be a key to future investigations in this field (Falomo et al 2000).

There are thus a number of investigations that have reported on high redshift host galaxies. Their interest as samples of high redshift galaxies in general has somewhat been overshadowed by the recent major progress in recognising and studying high redshift

non-QSO galaxies, via photometric redshifts and 10m telescope spectroscopy. However, the QSO environment is still of considerable interest in the context of the general galaxy population at higher redshifts.

As well as the redshifts above 1, I have selected host galaxy measurements over the redshift range below 1 to cover the redshift range down to the well-studied low redshift QSOs (Kotilainen et al 1998, Kotilainen and Falomo 2000) . The diagrams show the result, attempting to be comprehensive at higher redshifts, while selecting quantities derived with reliable methods and good data. They also do not impose any interpretation on the results, such as K-corrections, evolutionary assumptions, or extinction estimates. Given the different instrumental and observational limitations between the NIR and traditional optical bands, I have compiled (or applied corrections to obtain) the data for H-band and I-band. These are shown in the plots.

In addition to the studies referenced, a number of these are from ongoing and unpublished work of my own at the time of writing. They include NIR and optical data from CFHT with AO correction, and some HST WFPC2 data. The plots also show for comparison, selected points for low redshift QSOs, which I think are representative, but not at all complete, since there are hundreds of low redshift QSO hosts in the literature. The plots also distinguish between radio-loud and radio-quiet objects, since this is likely to be a fundamental and diagnostic difference. All points shown are derived for H_0=50 and q_0=0 cosmology. This is for easiest comparison rather than to represent a preferred choice.

While the comparison of results for the same objects from different investigators are encouraging in the few available instances, it is likely that both scatter and systematic differences arise from the different methods of removing PSFs, and overall image quality differences. I have omitted data that are less reliable - usually from poor resolution, smaller telescopes, or more noisy detectors. As a rough guide, the table shown compares the 'quality' of data from different sources. There are two important criteria in data for host galaxy studies: detection of faint extended flux, and image resolution to minimise the nuclear point source spread. Different telescopes have different strengths in these two areas, and there are additional criteria of detector noise and PSF complexity. Adding error bars to the diagrams to take all these into account would be a large and unrewarding task, so I am assuming that the mix of different investigations in overlapping redshifts will show the overall trends without severe systematic errors.

Nothwithstanding these caveats, there are some clear points in the plots. Generally, the host galaxies are more luminous with increasing redshift. The increase is faster with redshift in visible wavelengths, and larger in the NIR in the radio-loud sources. However, the wavelength dependence is strongly affected by the redshift itself, as well as evolution

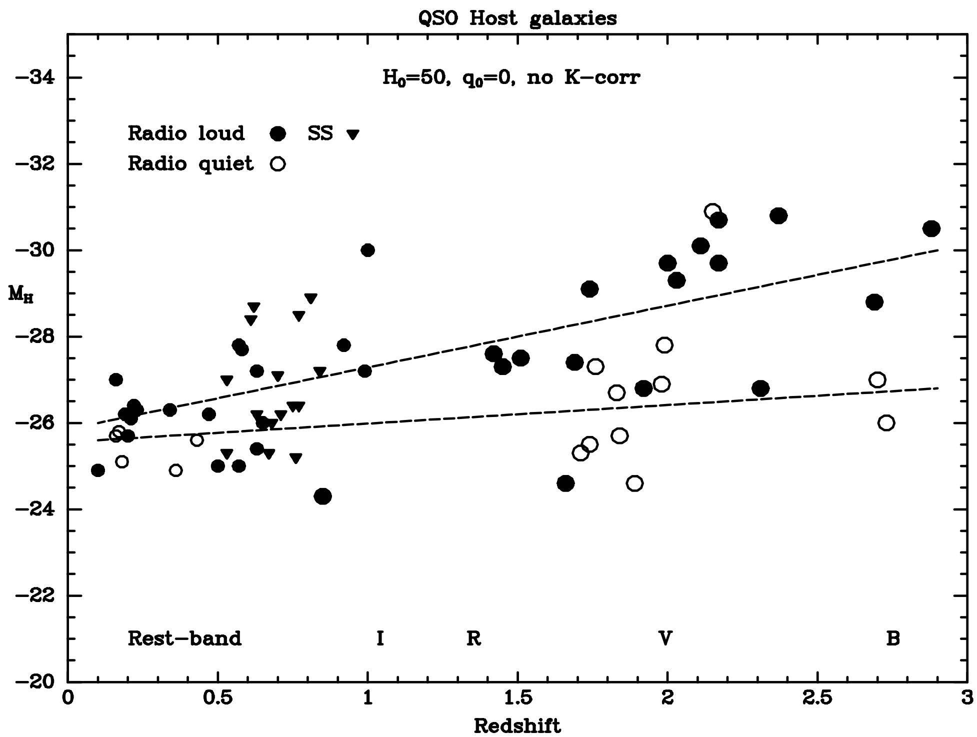

Fig. 1.— H-band absolute magnitudes of resolved host galaxies, as labelled. All values are for given cosmology and have no K-correction, and some have been derived from J or K band observations. z<0.3 points refer to samples rather than individual objects, but are representative. The dotted lines are linear fits to the radio-loud and radio-quiet data as plotted. The rest wavelength bandpasses are given along the bottom.

in the SED. I have sketched in linear suggestions for the trends as observed. As noted by Falomo et al, at redshifts 1 and above, the radio-loud hosts are brighter than BCGs and L* galaxies, while radio-quiet ones are comparable with BCGs. All are unusually bright galaxies, and there a few enough null detections that this is unlikely to be an observational issue.

What can we infer from these results? Given that the observed rest wavelength changes with redshift as shown along the X-axes, the host galaxies are bluer as well as brighter, consistent with passive evolution or declining star-formation as time proceeds, and the hosts at redshifts 2 and higher are starburst objects. This has been noted by various workers. However, since QSO episodes are short compared with the lifetimes of galaxies, we are not necessarily seeing the evolution of a population of galaxies, but may also be looking at a changing population of hosts with time. We come back to this below.

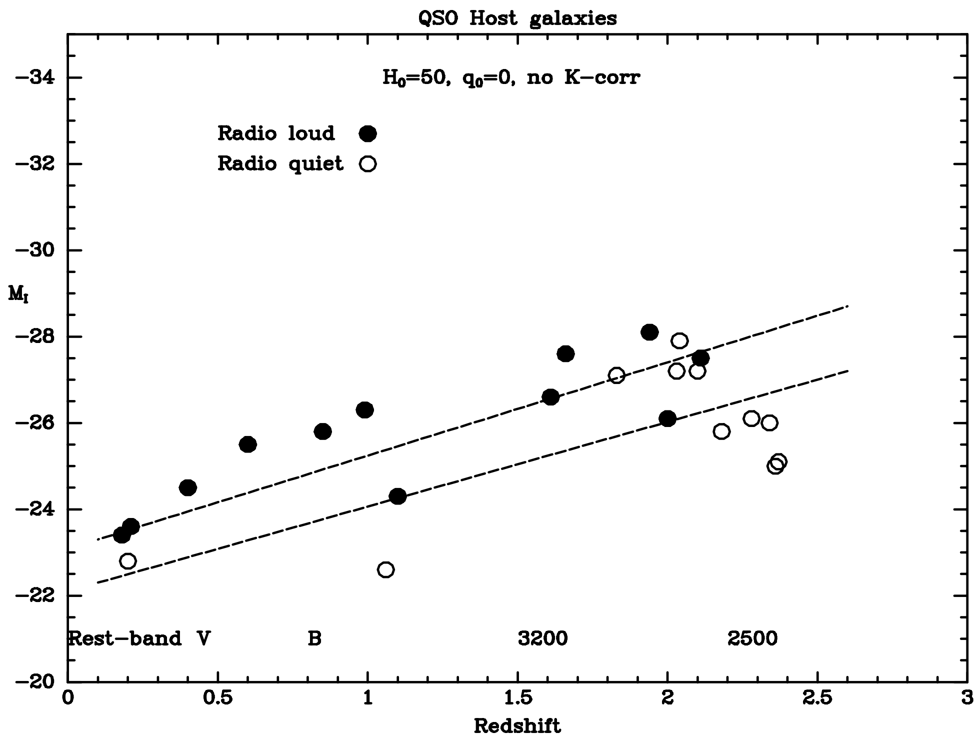

Fig. 2.— I-band absolute magnitudes as in figure 1

As galaxy luminosity can reflect star-formation activity, increased content by merging, or stripping by tidal events, we can remove some parameters by looking at the average colours indicated by the lines through the H and I band plots. The colour plot shows this evolution for the two QSO types. We show for comparison the colour expected for constant star-formation, and passive evolution from starburst for galaxy formed at redshift about 4, with the adopted cosmology timescale. Dust and increased metallicity move the plots vertically up the diagram.

The colour evolution is different for the two QSO types. At high redshift, both have colours of star-forming galaxies, but the radio-loud ones have an older population present. The radio-quiet hosts appear to evolve passively to redshift 1, and then are reddened by abundance changes and/or dust. The radio-loud hosts appear to have active star-formation at high levels down to redshift near 0.5, and then go the way of the radio-quiet.

The scale lengths are more subject to differences in PSF removal, but the plot shows what the best data indicate. Generally, the high redshift host galaxies are smaller, and become much smaller than present-day bright galaxies. There is a scatter of high values that may arise from tidal tails. If so, this is seen predominantly at redshifts 0.5 to 1.

Table 1: Comparative power of investigations

NIR				CCD				
Telescope	Res(")[a]	Det[b]	PSF[c]	Telescope		Res(")	Det	PSF
VLT	0.5	230	50	CFHT	HRCAM	0.4	12	3
CFHT AO	0.15	91	60		AO	0.3	47	15
HST	0.15	100	40	HST	WFPC2	0.1	4-20	4-20
ESO	0.8	30	4		STIS	0.1	30	30
				KPNO		1.3	17	1
				WHT		0.7	88	12

[a] RES (") Image FWHM in arcsec
[b] Det = S/N achieved (Aperture x thruput x exp / noise)
[c] PSF = Goodness of PSF removal (Det x 0.1 / FWHM)

(when galaxy merging is generally known to be higher). This is consistent with heriarchical merging as galaxies evolve, as noted by other authors in the subject. It is also consistent with the evolution of non-active galaxies as seen by Lyman-break galaxy studies.

2. Cluster environment

There have been several studies of QSO galaxy companions. Many authors have noted the apparent connection between galaxy interactions and QSO activity, as well the signs of past tidal events in the profiles of QSO hosts at low redshift. These are much harder to see at high redshift, since tidal tails are old stars which are faint and close to the nuclear PSF. It is simpler to count and even get spectra for nearby companions, in order to characterise the galaxy environment of QSOs. However, such results are quite dependent on image quality, signal level, and detection threshold. The table again shows where we expect to do best in this regard.

The compendium of high redshift QSOs is shown in the Figure 5. The principal references for these are Hutchings et al 1995, Hutchings 1995a, Teplitz et al 1999, Wold et al 2000, 2001, Haines et al 2000, and some recent unpublished data of my own. The numbers plotted are estimated excess galaxies within 20 arcsec of the QSO in the sky, in some cases derived from different areas originally reported. The low-redshift values are means from many objects, and the vertical 'error bar' indicates the range among individual objects. A similar range is revealed at redshift 1.1, which is QSOs in the 'supercluster'

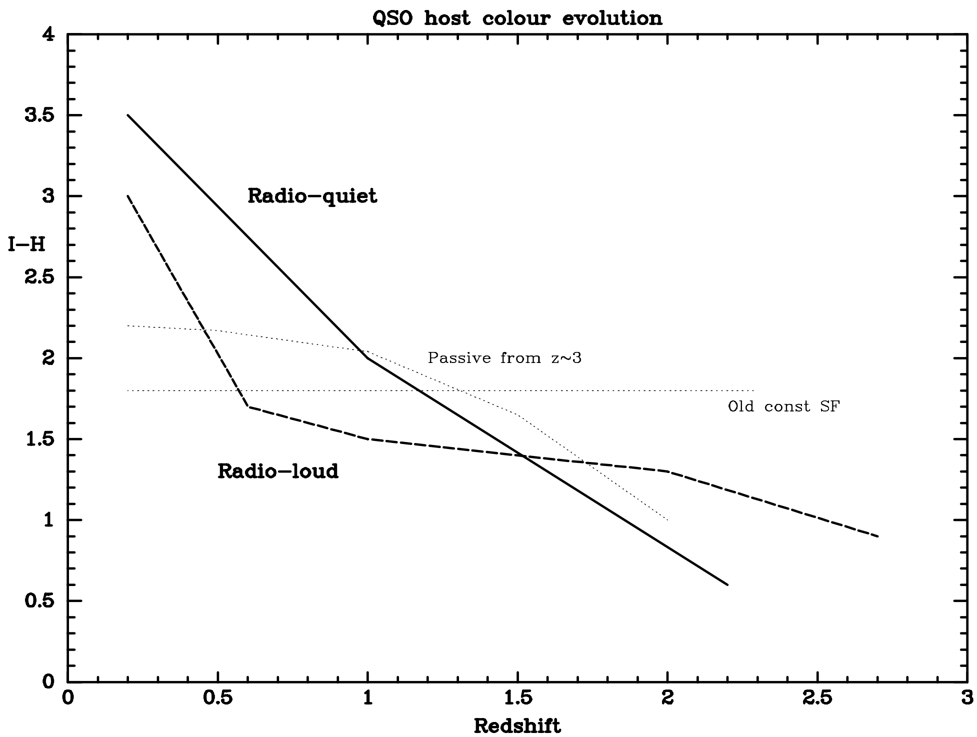

Fig. 3.— Locus of linear fits from Figures 1 and 2 converted to I-H. The faint dotted lines are approximations from Gissel93 models for measured I-H as observed redshift changes. (The constant observed colour for constant star-formation arises because slow reddening is balanced by the moving bandpasses.) Radio-loud hosts appear to arise in a population that is actively forming stars over z=0.8 to 2, while radio-quiet hosts have passivley evolving populations. The observed redder colours at low redshift may arise from dust or increasing metal abundance.

region discussed by Hutchings et al (1995). The dotted lines sketch in suggested increases in the RL and RQ environments above z=1. Clearly these are very uncertain in view of the scatter where we have enough measures to know. However, it is generally accepted that QSOs do live in regions of enhanced galaxy populations, and that the number of galaxy companions probably increases at higher redshift. Several investigations show that the companion density on the sky falls quickly with radius, so that the plot is oversimplified in that respect.

Another caveat is that at high redshift, the companions seen are compact, so that their detection depends on good signal and high resolution. The deepest detection of companions comes from long CCD exposures with HST. The small size of the faint galaxies means that

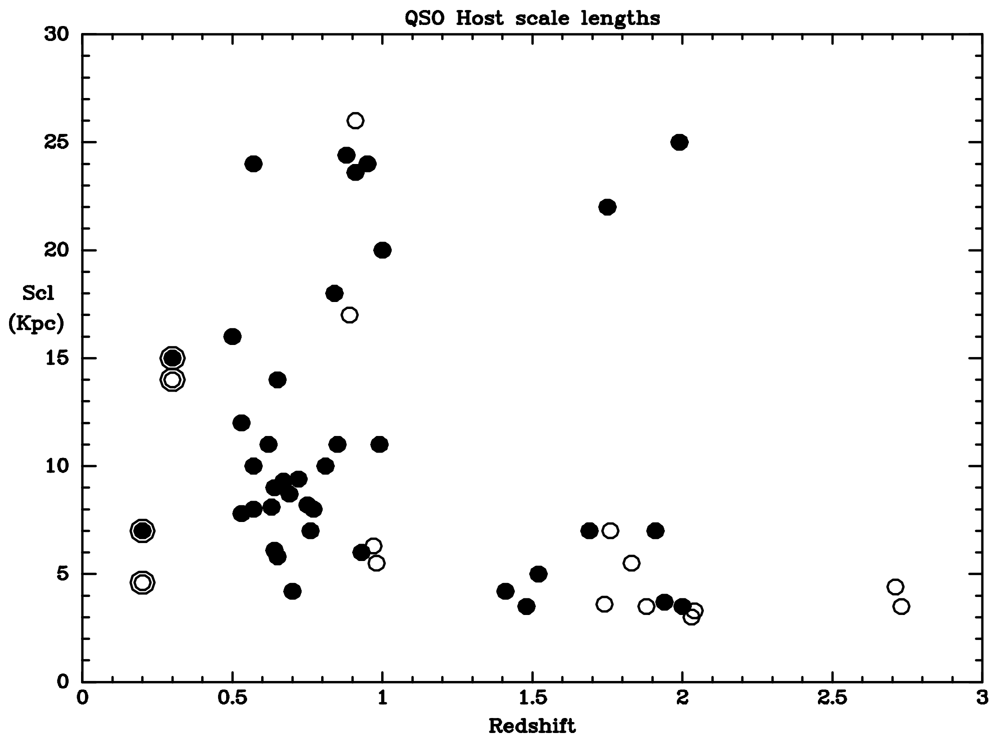

Fig. 4.— Host galaxy scale lengths for high redshift hosts, corrected for differences in published values of FWHM, enclosed flux fraction. The two low redshift points (circled) are for samples - the lower one being HST short exposure images, which do not detect faint outer parts of the galaxies.

HST can detect more of them, to a magnitude fainter than CFHT, for example. However, at magnitude fainter than 24, most galaxies are high redshift star-forming objects, so that their association with the QSO needs more than just blue colour from 2 filters. I have not plotted any of these very faint 'companions' in the diagram.

In the NIR, HST has the advantage of dark sky, but 8m class telescopes have so much more light-gathering power that they win - not only for companions but also the faint parts of host galaxies that indicate tidal events and evolved populations. However, no major investigations have been done yet.

The galaxy companions we know about, are different at high redshift, and suggestive of environments which may evolve into small groups (or a single large galaxy) at present time. The environment that triggers QSO activity almost certainly changes with cosmic time, ranging from initial merging of protogalaxies to tidal triggers involving gas at present time. Radio-loud sources are likely the more massive black hole (= galaxy bulge mass, age

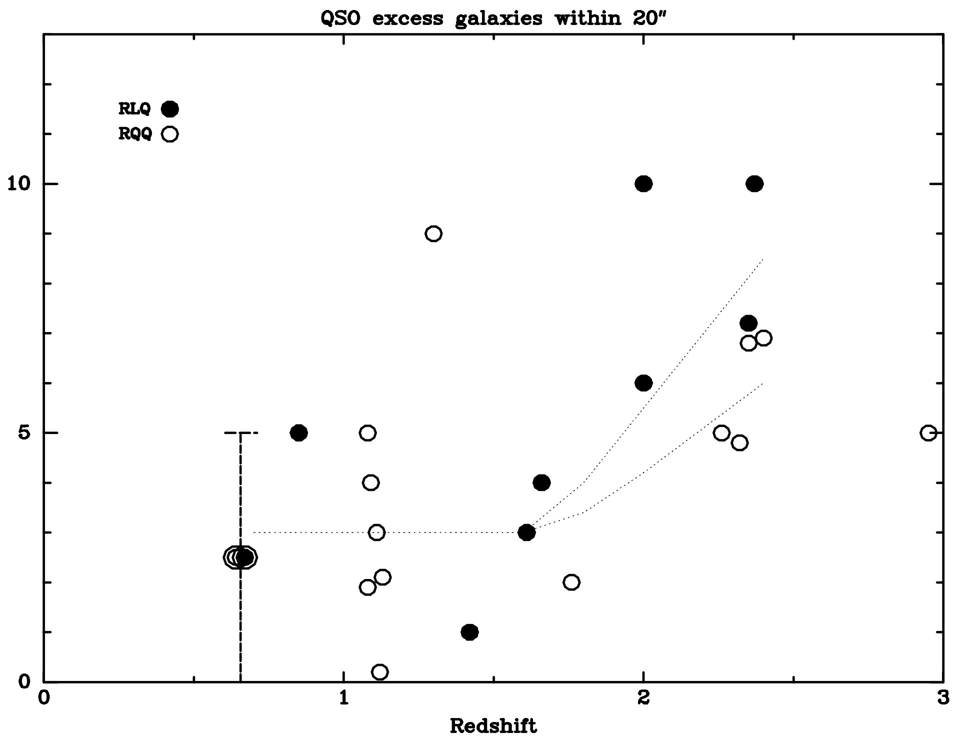

Fig. 5.— Counts of excess galaxies near QSOs. The values are corrected to refer to the same area of sky, and for differences in limiting magnitude. Dotted lines are suggested mean relationships for radio-loud and radio-quiet QSOs.

of galaxy, merging history,..?). It is also known in some cases that the companions are a foreground group, which may be connected with the QSO only by lensing action that makes the QSO more visible. We need more complete and careful investigations to get the required statistics on these issues.

3. Line emission

The classic paper on line emission from AGN at high redshift is some years ago, by McCarthy et al (1991). This established the 'alignment effect' between radio and emission-line structure that seems to be accepted as the ionising effect of nuclear radiation and jet activity on a gas-rich environment. For low redshift QSOs, there is another famous paper by Stockton and MacKenty (1987) that investigates line emission, and finds extended and irregular emission line gas predominantly in extended radio-loud QSOs. This reveals the presence and complex dymanics of gas that lies well outside the stellar population and

is presumably the result of tidal events that have fuelled the nucleus.

Work on radio-quiet high redshift QSOs has occured only recently, again with the help of larger telescopes, NIR detectors, and AO. Ohta et al (2000) have detected [O II] emission in a z=4.7 QSO, and Hutchings et al (2000) find [O III] and Hα in a sample of radio-quiet or compact radio source QSOs. These all have line emission that lies within the host galaxy and thus corresponds to the NLR gas that has been mapped in low redshift Seyferts and QSOs. Where there is radio structure in these objects. the line emission is aligned with it. The emission line images indicate line equivalent widths typically 200 - 300Å in the redshifted frame, of which about half is typically from the nucleus.

More detailed work will extend this work to a more statistically significant sample and perhaps lead to an understanding of the internal dynamics of the high redshift host galaxies.

4. Summary

This review cannot do justice to the details of the different investigations. Other papers in this volume deal with individual programs, which are included in my summary plots.

Overall, the work of the past decade has established a credible set of investigations of high redshift QSO hosts and environments. This should become more detailed and extend to higher redshift with 8m class telescopes with AO, and advanced HST (and NGST) instrumentation. It seems well established that host galaxies at high redshift are luminous, with active star-formation, and generally are very compact for their luminosities. They also live in dense galaxy companion environments. The hosts and their companions must undergo significant merging and evolution, as the much less common present-epoch QSOs are found in larger hosts with less crowded environments. We are on the brink of studying the formation and evolution of the central black holes, which can be measured by the host spheroid morphology, and the nuclear BLR profiles. It is clear that the formation and triggering of QSOs is an integral part of the formation of galaxies, and that QSOs at high redshift offer a wealth of cosmological information for the years to come.

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